

LEPTON NUMBER AND LEPTON FLAVOR VIOLATIONS IN SEESAW MODELS

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We discuss the impact of fermion mass matrices on some lepton number violating processes, namely baryogenesis via leptogenesis and neutrinoless double beta decay, and on some lepton flavor violating processes, namely radiative lepton decays in supersymmetric seesaw models.

I. INTRODUCTION

A breakthrough in particle physics happened in 1998, when the SuperKamiokande Collaboration announced evidence for oscillation of atmospheric neutrinos [1]. Recently, at the Sudbury Neutrino Observatory (SNO), evidence for flavor conversion of solar neutrinos has been found [2], pointing towards oscillation of solar neutrinos too. These two important results come after a long series of experiments.

The most natural explanation of neutrino oscillations is that neutrinos have masses, and leptons mix just like quarks do. In this case, neutrino mass eigenstates ν_i are related to neutrino flavor eigenstates ν_α by the unitary transformation $\nu_\alpha = U_{\alpha i} \nu_i$, where U is the lepton mixing matrix [3].

It turns out that neutrino masses are very small with respect to charged lepton and quark masses. This fact can be accounted for in a simple and elegant way by means of the seesaw mechanism [4], which requires only a modest extension of the minimal standard model, namely the addition of the right-handed neutrinos.

As a consequence of this inclusion, a Yukawa term generating a Dirac mass term for the neutrino is allowed. Moreover, a Majorana mass term for the right-handed neutrino is also allowed. While the Dirac mass, m_ν , is expected to be of the same order of magnitude as the quark or charged lepton mass, the Majorana mass of the right-handed neutrino, m_R , is not constrained and thus may be very large. If this case occurs, a small effective Majorana mass for the left-handed neutrino, $m_L \simeq (m_\nu/m_R)m_\nu$, is generated.

In this framework, lepton flavors and lepton number are not conserved. The amount of lepton flavor violations may be very different, according to supersymmetric (SUSY) or nonsupersymmetric (nonSUSY) models. In fact, in nonSUSY models, due to the smallness of neutrino masses, lepton flavor violations are so small to be unobservable [5]. Instead, in SUSY models with universal soft breaking terms, lepton flavor violations can get much enhanced with respect to nonSUSY models [6].

On the other hand, the seesaw mechanism allows for lepton number violations, such as the neutrinoless double beta decay and the right-handed neutrino decay. The latter may be involved in the generation of the baryon asymmetry in the universe, through the baryogenesis via leptogenesis mechanism [7]. In fact, the lepton asymmetry produced by the decay of heavy right-handed neutrinos is partially converted into a baryon asymmetry by electroweak sphaleron processes [8].

In the present paper, we discuss both lepton number and lepton flavor violations in nonSUSY and SUSY seesaw models, especially in connection with fermion mass matrices. We consider some explicit models for mass matrices and determine the implications for the baryogenesis via leptogenesis, the neutrinoless double beta decay and the radiative

lepton decays in SUSY theories. In section II we summarize the experimental informations on neutrino masses and lepton mixings. In section III the seesaw mechanism is briefly discussed. In section IV and V we outline the link between mass matrices, leptogenesis and radiative lepton decays in SUSY models. Finally, in section VI, we comment on the results.

II. NEUTRINO MASSES AND MIXINGS

From the combined study of atmospheric, solar and also reactor neutrinos we get a nearly bimaximal form for the mixing matrix,

$$U \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \epsilon \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad (1)$$

where $\epsilon \lesssim 0.1$. The name bimaximal comes from the fact that both $U_{\mu 3}$ and $U_{e 2}$ have the value $1/\sqrt{2}$, while $U_{e 3}$ is very small. However, the best fit is closer to

$$U \simeq \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \epsilon \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \quad (2)$$

The element $U_{\mu 3}$ is determined by atmospheric oscillations, with a mixing angle nearly maximal. The element $U_{e 2}$ by solar oscillations, with a mixing angle large but not maximal. The smallness of element $U_{e 3}$ is obtained from reactor neutrinos [9].

These studies also provide values for square mass differences of left-handed neutrinos. From atmospheric neutrinos we get

$$|m_3^2 - m_2^2| \sim 10^{-3} \text{eV}, \quad (3)$$

and from solar neutrinos (LMA solution)

$$|m_2^2 - m_1^2| \sim 10^{-5} \text{eV}, \quad (4)$$

or less favoured (LOW solution)

$$|m_2^2 - m_1^2| \sim 10^{-7} \text{eV}. \quad (5)$$

Other two experimental informations come from single beta decay [10],

$$m_{\nu_e} = (|U_{ei}|^2 m_i^2)^{1/2} < 2.5 \text{ eV}, \quad (6)$$

and neutrinoless double beta decay [11],

$$M_{ee} = U_{ei}^2 m_i \lesssim 0.38 \text{ eV}. \quad (7)$$

The process of neutrinoless double beta decay is allowed only if neutrinos are Majorana particles, thus evidence for it would support the seesaw mechanism.

Due to the property $|m_2^2 - m_1^2| \ll |m_3^2 - m_2^2|$, three types of hierarchies for left-handed neutrinos are possible. In the normal hierarchy $m_3 \gg m_2, m_1$, with a complete hierarchy for $m_2 \gg m_1$. In this case $m_3^2 \sim 10^{-3} \text{ eV}^2$ and $m_2^2 \sim 10^{-5} \text{ eV}^2$ (or $m_2^2 \sim 10^{-7} \text{ eV}^2$). The partially degenerate spectrum is obtained for $m_2 \simeq m_1$. In the inverse hierarchy, $m_1 \simeq m_2 \gg m_3$, we get $m_{1,2}^2 \sim 10^{-3} \text{ eV}^2$. Finally, for the nearly degenerate spectrum we have $m_1 \simeq m_2 \simeq m_3 \sim 0.1 - 1 \text{ eV}$, because of relations (6) and (7).

In general, the lepton mixing matrix can be parametrized as the standard form of the quark mixing matrix (including a phase δ), times a diagonal phase matrix, like $P = \text{diag}(e^{i\varphi_1/2}, e^{i\varphi_2/2}, 1)$. Sometimes a simplified approach is useful, namely to consider m_1, m_2 to be positive and negative, neglecting phases φ_1, φ_2 . In a similar way one can take ϵ positive or negative, and neglect the phase δ . Negative masses $m_{1,2}$ correspond to phases $\varphi_{1,2} = \pi$.

III. SEESAW MECHANISM

For three generations of fermions the seesaw formula is given by

$$M_L \simeq M_\nu M_R^{-1} M_\nu^T, \quad (8)$$

where M_ν is the Dirac neutrino mass matrix, M_R the right-handed neutrino mass matrix and M_L the left-handed (effective) neutrino mass matrix. Some problems with naturalness may happen. In fact, if M_ν is highly hierarchical, as quark or charged lepton mass matrices are, then it is unnatural to obtain nearly degenerate neutrinos.

From the experimental informations on neutrino masses and mixings we can infer the possible forms of the effective neutrino mass matrix through the formula

$$M_L = U D_L U^T, \quad (9)$$

where D_L is the diagonal of effective neutrino masses. This relation is valid in the basis with the charged lepton mass matrix diagonal, $M_e = D_e$. However, for M_e nearly diagonal,

the approximation (9) can be adopted because of the bilarge lepton mixing. In fact, the difference between matrices (1) and (2) could be due to the contribution of the charged lepton mass matrix [12] or to a running effect from a high scale [13]. We are interested in determining the form of the heavy neutrino mass matrix through the inverse seesaw formula

$$M_R \simeq M_\nu^T M_L^{-1} M_\nu. \quad (10)$$

Note that the matrix M_L^{-1} can be obtained from M_L by changing m_i with $1/m_i$, because $M_L^{-1} = U D_L^{-1} U^T$. As a first step we may assume symmetric matrices and quark-lepton symmetry,

$$M_e \sim M_d \sim \text{diag}(m_d, m_s, m_b), \quad (11)$$

$$M_\nu \sim M_u \sim \text{diag}(m_u, m_c, m_t). \quad (12)$$

The first quark-lepton relation is indeed a good approximation, while the second one is only an assumption.

IV. LEPTON NUMBER VIOLATION

If we consider the seesaw mechanism, we have light (left-handed, effective) and heavy (right-handed) Majorana neutrinos and hence the violation of total lepton number. The neutrinoless double beta decay is allowed, with $M_{ee} = M_{L11}$. Moreover, as a consequence of electroweak sphaleron processes, the lepton number violation can be converted into a baryon number violation. Then, the baryogenesis via leptogenesis mechanism was proposed [7,14] where the out-of-equilibrium decays of heavy neutrinos produce a lepton asymmetry which is transformed into a baryon asymmetry by sphaleron processes.

In the baryogenesis via leptogenesis mechanism, the baryon asymmetry is given by

$$Y_B \simeq \frac{1}{2} \frac{1}{g^*} d \epsilon_1, \quad (13)$$

with the CP violating asymmetry in the decay of the lightest heavy neutrino with mass $M_1 \ll M_2 < M_3$ given by

$$\epsilon_1 \simeq \frac{3}{16\pi v^2} \left[\frac{[(M_D^\dagger M_D)_{12}]^2}{(M_D^\dagger M_D)_{11}} \frac{M_1}{M_2} + \frac{[(M_D^\dagger M_D)_{13}]^2}{(M_D^\dagger M_D)_{11}} \frac{M_1}{M_3} \right], \quad (14)$$

where $M_D = U_e^\dagger M_\nu U_R$, with U_R diagonalizing M_R and U_e diagonalizing M_e . The parameter $v \simeq m_t$ is the VEV of the Higgs doublet. The factor d in (13) is a dilution factor which depends on M_1 and especially on

$$\tilde{m}_1 = \frac{(M_D^\dagger M_D)_{11}}{M_1}. \quad (15)$$

Minor dilution, $d \sim 10^{-1}$ is achieved for $\tilde{m}_1 = 10^{-5} - 10^{-2}$ eV, while outside this range the dilution factor drops [15]. Primordial nucleosynthesis requires Y_B to lie between 10^{-11} and 10^{-10} (see for example Ref. [16]).

We consider realistic mass matrices, expressed in terms of the Cabibbo parameter $\lambda = 0.22$ and the overall mass scale,

$$M_e \sim \begin{pmatrix} \lambda^6 & \lambda^3 & \lambda^5 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} m_b, \quad (16)$$

$$M_\nu \sim \begin{pmatrix} \lambda^{12} & \lambda^6 & \lambda^{10} \\ \lambda^6 & \lambda^4 & \lambda^4 \\ \lambda^{10} & \lambda^4 & 1 \end{pmatrix} m_t, \quad (17)$$

based on both $U(2)$ horizontal symmetry and quark-lepton symmetry (see Ref. [17] and references therein).

For the complete normal hierarchy (and also the inverse hierarchy and the partially degenerate spectrum with $m_2 > 0$) we get

$$M_R \sim \begin{pmatrix} \lambda^{12} & \lambda^{10} & \lambda^6 \\ \lambda^{10} & \lambda^8 & \lambda^4 \\ \lambda^6 & \lambda^4 & 1 \end{pmatrix} \frac{m_t^2}{m_1}, \quad (18)$$

consistent with the $U(2)$ symmetry [17], and

$$\epsilon_1 \sim \frac{3}{16\pi} \left(\frac{\lambda^{20}}{\lambda^{12}} \lambda^4 + \frac{\lambda^{12}}{\lambda^{12}} \lambda^{12} \right) \sim 10^{-10}, \quad (19)$$

with $\tilde{m}_1 \sim m_1$, providing $Y_B \sim 10^{-14}$. The overall mass scale of M_R is larger than 10^{15} GeV, which is close to the unification scale.

For the partially degenerate spectrum with $m_2 < 0$ and $m_1 \simeq \epsilon m_3$, so that $(M_L^{-1})_{33} \sim 0$, we have

$$M_R \sim \begin{pmatrix} \lambda^{10} & \lambda^6 & \lambda^4 \\ \lambda^6 & \lambda^4 & 1 \\ \lambda^4 & 1 & \lambda^2 \end{pmatrix} \lambda^6 \frac{m_t^2}{m_1}, \quad (20)$$

$$\epsilon_1 \sim \frac{3}{16\pi} \left(\frac{\lambda^{16}}{\lambda^{12}} \lambda^4 + \frac{\lambda^{12}}{\lambda^{12}} \lambda^4 \right) \sim 10^{-4}, \quad (21)$$

with $\tilde{m}_1 \simeq \lambda^2 m_1$, so that high baryon asymmetry is achieved. Here the overall mass scale of M_R is larger than 10^{11} GeV, close to an intermediate scale.

If a moderate hierarchy in M_ν is adopted, for example

$$M_\nu \sim \begin{pmatrix} \lambda^6 & \lambda^3 & \lambda^5 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} m_t, \quad (22)$$

we obtain

$$M_R \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \frac{m_t^2}{m_1}, \quad (23)$$

$$\epsilon_1 \sim \frac{3}{16\pi} \left(\frac{\lambda^{10}}{\lambda^6} \lambda^2 + \frac{\lambda^6}{\lambda^6} \lambda^6 \right) \sim 10^{-6}, \quad (24)$$

with $\tilde{m}_1 \sim m_1$, providing $Y_B \sim 10^{-10}$. The overall mass scale of M_R is again larger than 10^{15} GeV, close to the unification scale.

Thus we have considered three distinct models for lepton mass matrices [18]. Model I is based on matrices (16), (17), (18), model II on matrices (16), (17), (20), and model III on matrices (16), (22), (23). Models I and III have M_R nearly diagonal at the high scale, while the model II has a roughly offdiagonal M_R at the intermediate scale. Models II and III are reliable for leptogenesis, while model I gives a too small asymmetry. Moreover, due to the value $m_2 < 0$, model II leads to a suppression of the rate for neutrinoless double beta decay, $M_{ee} \sim 10^{-4} - 10^{-3}$ eV, while models I and III yield $M_{ee} \sim 10^{-3} - 10^{-2}$ eV for the normal hierarchy and $M_{ee} \sim 10^{-2} - 10^{-1}$ eV for the inverse hierarchy. The link between leptogenesis and lepton mass matrices is discussed in many papers, see for example Ref. [19].

V. LEPTON FLAVOR VIOLATION

In SUSY seesaw models with universality above the heavy neutrino mass scale, lepton flavor violations are induced, which depend on the parameters

$$C_{ij} = \frac{1}{v^2} (M_D^\dagger)_{ik} \ln \frac{M_U}{M_k} (M_D)_{kj}, \quad (25)$$

where M_U is the universality scale. In fact, in SUSY models with soft breaking terms, there are lepton flavor violating terms in the offdiagonal elements of slepton mass matrices and trilinear couplings. If such violations occur at the tree level, the branching ratios exceed the experimental bounds. Therefore, it is usually assumed that lepton flavor violations do not occur at the tree level, and this is realized by assuming universality, that is slepton mass matrices and trilinear couplings proportional to the unit matrix, as happens in minimal supergravity. However, lepton flavor violations are generated by the effect of renormalization of Dirac neutrino Yukawa couplings from the universal scale to the right-handed neutrino scale [6]. The offdiagonal elements of the Dirac neutrino mass matrix induce offdiagonal elements in slepton mass matrices and trilinear couplings. In particular, the branching ratios for lepton flavor violating radiative processes $l_i \rightarrow l_j + \gamma$, where l stands for a charged lepton and γ for a photon, depend on the offdiagonal elements of slepton mass matrices, which in turn depend on the quantities C_{ij} . The subject has been studied in several papers, see for example Ref. [20]. Here we discuss the impact of the mass matrices of the previous section on radiative lepton decays. Note that the baryogenesis via leptogenesis and the radiative lepton decays have a different dependence on the neutrino mass matrix M_D .

For model I we get

$$U_e \sim \begin{pmatrix} 1 & \lambda & \lambda^5 \\ -\lambda & 1 & \lambda^2 \\ \lambda^5 & -\lambda^2 & 1 \end{pmatrix}, \quad U_R \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^6 \\ -\lambda^2 & 1 & \lambda^4 \\ \lambda^6 & -\lambda^4 & 1 \end{pmatrix}, \quad (26)$$

so that

$$M_D = U_e^\dagger M_\nu U_R \sim \begin{pmatrix} \lambda^7 & \lambda^5 & \lambda^5 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^6 & \lambda^4 & 1 \end{pmatrix} m_t. \quad (27)$$

We assume that cancellations between terms of the same order in λ do not occur. The calculation of C_{ij} gives

$$C_{12} \sim \lambda^{12} \ln \lambda^{12} + \lambda^{10} \ln \lambda^8 + \lambda^{10} \sim 10^{-7}, \quad (28)$$

$$C_{23} \sim \lambda^{10} \ln \lambda^{12} + \lambda^6 \ln \lambda^8 + \lambda^4 \sim 10^{-3}, \quad (29)$$

$$C_{13} \sim \lambda^{12} \ln \lambda^{12} + \lambda^8 \ln \lambda^8 + \lambda^6 \sim 10^{-4}. \quad (30)$$

For model II we have

$$U_R \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^6 \\ -\lambda^4 & 1 & \lambda^2 \\ \lambda^6 & -\lambda^2 & 1 \end{pmatrix}, \quad (31)$$

and

$$M_D \sim \begin{pmatrix} \lambda^7 & \lambda^5 & \lambda^5 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^6 & \lambda^2 & 1 \end{pmatrix} m_t, \quad (32)$$

which differs from matrix (27) only for the element 3-2, so that

$$C_{12} \sim \lambda^{12} \ln \lambda^4 + \lambda^{10} \ln \lambda^4 + \lambda^8 \sim 10^{-6}, \quad (33)$$

$$C_{23} \sim \lambda^{10} \ln \lambda^4 + \lambda^6 \ln \lambda^4 + \lambda^2 \sim 10^{-2}, \quad (34)$$

$$C_{13} \sim \lambda^{12} \ln \lambda^4 + \lambda^8 \ln \lambda^4 + \lambda^6 \sim 10^{-4}. \quad (35)$$

For model III we obtain

$$U_R \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}, \quad (36)$$

$$M_D \sim \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} m_t, \quad (37)$$

and then

$$C_{12} \sim \lambda^7 \ln \lambda^6 + \lambda^5 \ln \lambda^4 + \lambda^5 \sim 10^{-3}, \quad (38)$$

$$C_{23} \sim \lambda^6 \ln \lambda^6 + \lambda^4 \ln \lambda^4 + \lambda^2 \sim 10^{-2}, \quad (39)$$

$$C_{13} \sim \lambda^7 \ln \lambda^6 + \lambda^5 \ln \lambda^4 + \lambda^3 \sim 10^{-2}. \quad (40)$$

Generally, the dominant term is the third. However, sometimes the dominant term can be the second. Of course, each term has a coefficient of order 1 not indicated.

We have assumed that the universality scale is larger but of the same order of the heaviest right-handed neutrino mass. If $M_U \sim M_P$, the Planck mass, then C_{ij} is enhanced by about one order of magnitude. The experimental bounds on C_{ij} , inferred from Ref. [21], are given by $C_{12} \lesssim 10^{-3} - 10^{-1}$, $C_{23} \lesssim 10^{-1} - 10^2$, $C_{13} \lesssim 10^{-3} - 10^{-1}$, for large $\tan \beta$. Because of uncertainties in SUSY parameters, only wide ranges are available. Future sensitivities for C_{12} and C_{23} are expected to be lowered by one or two orders in next years. Due to theoretical and experimental uncertainties, we cannot make definite predictions. However, it is worth stressing that generally models favoured for leptogenesis predict higher values for C_{ij} , so that a positive signal could be found.

VI. CONCLUSION

We have performed on order-of-magnitude analysis of some lepton number violating processes, namely baryogenesis via leptogenesis and neutrinoless double beta decay, and some lepton flavor violating processes, namely radiative lepton decays in SUSY models. Three distinct kinds of model for mass matrices have been used. Generally, when leptogenesis is enhanced, also the rate of lepton decays is higher. Then, if lepton decays are not found, this would possibly imply another mechanism for baryogenesis or another mechanism for SUSY breaking, for example, instead of the gravity mediated SUSY breaking, the gauge mediated SUSY breaking [22].

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